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Technical report

Submersible Aircraft Concept Design Study – Amendment 1

Additional assessment of design risks & sensitivities within the original study, and an initial assessment of key control aspects

By

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The original *Submersible Aircraft Concept Design Study* (J. Eastgate and R. Goddard, NSWCCD-CISD-2010/011, August 2010) proposed a design to combines the speed and range of an airborne platform with the stealth of an underwater vehicle by developing a vessel that can both fly and submerge. The study proposed a design capable of insertion and extraction of Special Forces at greater ranges, higher speeds, and in locations not previously accessible without direct support from additional military assets.

The initial aim of this amendment was to develop an understanding of the control aspects of the proposed submersible aircraft concept, however in conducting this analysis a more detailed review of the key preliminary assumptions and their sensitivities was made, along with a re-assessment of the design tools used. This report summarizes the output of these reviews, highlights the key sensitivities identified, and shows a preliminary assessment of the control aspects of the concept design. This report is intended to supplement the original report, and act as reference to support future work and analysis into this concept.

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Executive Summary

The original Submersible Aircraft Concept Design Study(1) proposed a design that combines the speed and range of an airborne platform with the stealth of an underwater vehicle by developing a vessel that can both fly and submerge. The study proposed designs capable of insertion and extraction of Special Forces at greater ranges, higher speeds, and in locations not previously accessible without direct support from additional military assets.

The original study undertook a considerable level of analysis and design work within a relatively short period of time in order to produce a balanced design. To achieve this, a number of initial assumptions were made and a new design tool developed and as such a number of calculation/design risks were inherent in the initial design.

The initial aim of this additional short study was to develop an understanding of the control aspects of the proposed submersible aircraft concept; however, in conducting this analysis, a more detailed review of the key preliminary assumptions and their sensitivities was made along with a re-assessment of the design tools used.

This report summarizes the output of these reviews, highlights the key sensitivities identified, and shows a preliminary assessment of the control aspects of the concept design. This report is intended to supplement the original report and act as a reference to support future work and analysis into this concept.

. The following conclusions and recommendations are made:

- A further design iteration needs to be conducted to reflect the issues identified within this paper. This second design iteration should consider:
    - A review of key assumptions made reflecting the comments made in Section 3 of this paper to include, but not be limited to, the maximum take-off weight, take-off and cruising speeds, and altitude assumptions;

  - validation of the weight estimate focusing particularly on the estimates used for the hydraulic and battery systems;

  - changes to the wing design to reflect weight, speed and angle of attack issues highlighted in Section 3;

  - the potential integration of floats into the wing design.

- A further iteration of the in-air control analysis should be conducted reflecting any changes made in the further design iterations. This analysis should extend to consider issues such as lateral stability, longitudinal and lateral dynamics (e.g. assessing the aircrafts ability to recover from spin), and consider stall in more detail.

  - Initial assessment suggests that a split flap arrangement should offer the most flexible solution for the craft and that shorter flap lengths may produce the required control at a higher efficiency.

  - Noting the limitations of *Tornado* with respect to the unexplained coefficient of drag versus angle of attack plots and the inability to model spilt flap operations, alternative software and modeling solutions should be considered to undertake this analysis.

  - The potential to input designs into flight simulation software should also be considered. This would provide a more graphical way to visualize some of the control features and control performance.

Contents

List of Figures

List of Tables

List of Equations

Nomenclature

A	=	Aspect ratio
B	=	Fuselage width
b	=	Wingspan
C_d	=	Coefficient of drag
C_{D0}	=	Zero lift drag
C_f	=	Thrust coefficient
c.g.	=	Center of gravity
C_L	=	Coefficient of lift
C_l	=	Coefficient of roll moment
C_M	=	Coefficient of moment
C_{M0}	=	Airfoil moment coefficient of wing about the quarter chord
C_m	=	Coefficient of pitch moment
C_n	=	Coefficient of yaw moment
C_y	=	Coefficient side slip
C_{11}	=	Elasticity tensor
F_w	=	Wrinkle stress
H	=	Fuselage height
I_p	=	Structural pressure index
L	=	Fuselage length, Length
MAC	=	Mean aerodynamic chord
n_{limit}	=	Load factor limit
n_{ult}	=	Ultimate wing loading factor
p	=	Storage pressure
P	=	Maximum pressure differential
P_i	=	Internal pressure
r	=	Vessel internal radius, Radius
Re	=	Reynolds number
St	=	Static margin (stability factor)
S	=	Wing area, fuselage surface area
t	=	Skin thickness, Material thickness, mean chord
t_{root}	=	Root chord thickness

W	=	Fuselage weight
W_{to}	=	Maximum take-off weight
W_{wg}	=	Wing weight
W_{zf}	=	Zero fuel weight
a	=	Angle of attack
a_{total}	=	Total wing twist
a_{geo}	=	Geometric wing twist (washout)
a_{L}	=	Zero lift angle
σ_{θ}	=	Cylinder hoop stress
σ_{long}	=	Cylinder longitudinal stress
E	=	Young’s modulus
υ	=	Poisson ratio
l	=	Aspect ratio
U	=	Angle of sweep at the quarter chord line
Γ	=	Taper ratio
$\Lambda_{c/2}$	=	Wing sweep at the half chord

Notation

The axes notation for aircraft motions is shown in Figure 1.

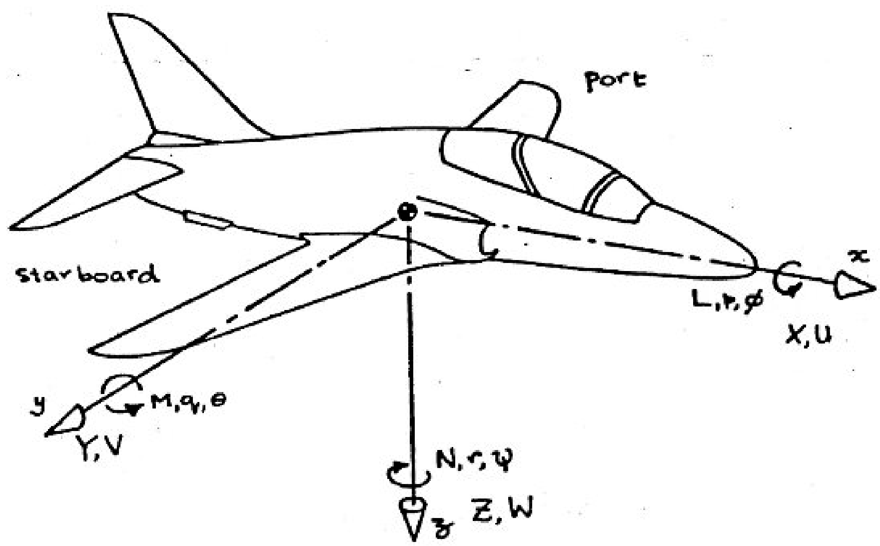

Figure 1 – Aircraft motion axes assumption

x	positive towards the nose of aeroplane
y	positive to starboard wing tip (i.e. right hand side looking in direction of flight)
z	positive downwards
φ	angular rotation about x; positive starboard wing tip down
θ	angular rotation about y; positive nose up
ψ	angular rotation about z ; positive nose to starboard
U	velocity component of centre of gravity along x
V	velocity component of centre of gravity along y
W	velocity component of centre of gravity along z
p	angular velocity about x (i.e. roll), positive starboard wing tip down
q	angular velocity about y (i.e. pitch), positive nose-up

r angular velocity about z (i.e. yaw), positive nose to starboard

The external forces acting on the aeroplane are X, Y and Z along x, y and z axes respectively. The moments of the external forces are L, M and N, i.e. roll, pitch and yaw respectively.

1. Introduction and Background

The original Submersible Aircraft Concept Design Study[(1)] proposed a design to combine the speed and range of an airborne platform with the stealth of an underwater vehicle by developing a vessel that can both fly and submerge. The study proposed designs capable of insertion and extraction of Special Forces at greater ranges, higher speeds, and in locations not previously accessible without direct support from additional military assets.

The initial aim of this amendment to the original study was to develop an understanding of the control aspects of the proposed submersible aircraft concept. However, in conducting this analysis, a more detailed review of the key preliminary assumptions and their sensitivities was made along with a re-assessment of the design tools used.

This report summarizes the output of these reviews, highlights the key sensitivities identified, and shows a preliminary assessment of the control aspects of the concept design. This report is intended to supplement the original report and act as a reference to support future work and analysis into this concept.

2. Overview of Original Assumptions and Models

Table 1 lists the initial requirements that were used to design the submersible aircraft concept in the original study. These were defined at the beginning of concept development. In particular, it should be noted that take-off speed was assumed, rather than calculated, based on the evolving design.

OPERATIONAL REQUIREMENTS		
Crew	2	men
Special Forces	6	men
Flight Range	800	miles
Surface Endurance	4	hours
Submerged Transit Range	12	nm
Loiter Endurance	72	hours
Cruise Speed	200 [89.4]	mph [$m.s^{-1}$]
Assumed Take-Off Speed	100 [51.4]	knots [$m.s^{-1}$]
Submerged Speed	6	knots
Operating Depth	30 [98.4]	meters [feet]

Table 1 – Original study design requirements(1)

The concept was developed using a range of tool-sets. The *Flying Submersible Design Tool* was developed within Excel specifically for the project and was used to estimate/ assess:

- A range of propulsion options;
- The selection of the airfoil section;
- The overall wing sizes;
- Pressure hull sizing;
- The design of the proposed inflatable float hulls;
- Overall weights and volumes;
- Vessel trim;

- The submerged drag of the vessel.

In addition, a range of commercial software tools were used:

- *Rhino* – A 3D CAD tool; used to model the concept design.
- *Xfoil* – A program written in Fortran for the design and analysis of 2D airfoils – used in the selection of airfoils for the submersible aircraft.
- *Tornado*– A program written for *Matlab* which was used to verify the initial design and airfoil selection.

3. Review of Key Assumptions

The *Flying Submersible Design Tool* is a complex spreadsheet reflecting the unique design of such a vehicle. It references many values and assumptions and incorporates a number of macros to optimize elements of the design.

In developing models of the concept for analysis of its in-flight controllability (Section 4), a number of uncertainties and design risks were identified within the original assumptions and calculations. This section discusses the identified issues, identifies their impact on the overall design and, where possible, proposes alternative assumptions.

3.1 Cruise Angle of Attack

The angle of attack is the angle the chord line of an airfoil makes with the oncoming air. Cruise angle of attacks for aircraft are typically 2-3 degrees, therefore the angle of attack calculated for the submersible aircraft appears to be sensible. However, the values for Maximum Take-Off Weight (MTOW), velocity and altitude used in the initial calculation are not realistic. This section discusses the reasons for this and proposes alternative values. Using these proposed alternative assumptions, the angle of attack for the current wing design rises to 4.7 degrees. To reduce this angle, additional consideration of the fundamental wing design will be required.

Putting the value of mass (m), density (ρ), wing area (S) and velocity (V) into Equation 1 and assuming the effect of the angle of attack (α) is negligible allows a value for the Coefficient of Lift (C_L) to be calculated. This is then used in *Tornado* to calculate the angle of attack of the craft.

$$C_L = \frac{L}{\frac{1}{2}\rho V^2 S} = \frac{mg\cos\alpha}{\frac{1}{2}\rho V^2 S}$$

Equation 1 – Coefficient of lift (C_L) formula

In order to calculate the angle of attack at cruise, MTOW has been used. This is an overestimation as, realistically, the aircraft would burn fuel during taxi, take-off and climbing. However, the difference in calculated angle of attack was minimal (2.5 degrees at a C_L of 0.1682 compared to 2.7 degrees at a C_L of 0.1825). As this difference was small, the originally calculated MTOW was retained for ease and continuity.

The original concept used the variables under the heading ‘Initial’ in Table 2 as the basis for design calculations. These numbers, however, contain a degree of risk associated with the assumptions made. A review of each of these assumptions is detailed below. The main risks in the design calculations are:

MTOW

The concept was frozen at a mass of 36,500 lbs (16.56 tonnes). In reviewing the data used to calculate this mass, it was concluded that the value for the mass of the High-Pressure (HP) air system was unrealistic. Using a more realistic HP system mass, the overall mass of the concept is estimated to be approximately 45,336 lbs (20.58 tonnes).

Velocity

A take-off velocity of 100 $m.s^{-1}$, rather than desired 100 knots, was wrongly used in the initial calculations.

Altitude

A cruise altitude at sea level was assumed in all lift calculations. The design requirements set a cruise altitude of 5,000 ft (1,524 m).

The higher MTOW, and cruise altitude and velocity are shown under the heading ‘Updated’ in Table 2.

	Initial	Updated	Units
MTOW	36,500	45,340	lbs
Speed (*V*)	223.7 (100)	200 (89.41)	mph ($m.s^{-1}$)
Altitude	0 (0)	5,000 (1,524)	ft (m)

Table 2 – A Summary of the initial and updated design variables

A sensitivity analysis was conducted to determine the effect that changing these variables would have on the overall concept (specifically Variant 1 detailed in the original report (1)). Table 3 shows the effect that changing the values for speed and altitude has on the cruise angle of attack.

Wing planform area (m^2)	Speed ($m.s^{-1}$)	Altitude (m)	Density (kg/m^3)	Weight (kN)	C_L	Angle of Attack from *Tornado* (Degrees)
145.6	89.4	1,524	1.056	162.06	0.2638	**3.8366**
145.6	100.0	1,524	1.056	162.06	0.2109	**3.0818**
145.6	89.4	0	1.225	162.06	0.2273	**3.3161**

Table 3 – Sensitivity assessment for altitude and speed

Table 4 shows the cruise angle of attack for two different situations; one where all the '**Initial**' variables are used and the other with all the '**Updated**' variables. As discussed, typical values of angle of attack in the cruise mode are generally between 2 and 3 degrees. The increased mass and lower velocity used in later calculations results in more lift being required that initially calculated and, therefore (for the given design), a higher angle of attack is necessary to produce the required lift. Two different aerofoil sections were used in the original concept; the root is based on sections EH2010 and the wing tips have the section E186. These reflex type airfoils have a lower max C_L. Therefore, these higher angle of attacks are not desirable.

Data	Wing planform area (m^2)	Speed ($m.s^{-1}$)	Altitude (m)	Density ($kg.m^{-3}$)	Weight (kN)	C_L	Angle of Attack from Tornado (Degrees)
Initial	145.6	89.4	1,524	1.056	20.22	0.3290	**4.7687**
Updated	145.6	100.0	0	1.225	16.21	0.1825	**2.6776**

Table 4 – Comparison of calculated angle of attack

In order to keep C_L low (and therefore, the angle of attack nearer the originally calculated values for the larger predicted mass), velocity and/or wing area could be increased. It is likely to be more feasible to increase the overall wing area. It should be noted that the control surface analysis in *Tornado* would need to be repeated to reflect a change in either parameter (Section 4).

Alternatively, the airfoil section could be changed to one with a higher maximum C_L, thereby allowing a higher cruise angle of attack. If this approach was taken, the craft would have to consider the use of a computerized active flight control system; removing the reflex airfoil eliminates the natural stability of the aircraft.

3.2 Take-Off Speed

Take-off and cruise speeds are important in defining the flight envelope of the aircraft. Climb speeds and approach speeds are defined from these along with the aircraft's stall speed.

The take-off speed assumption in the original study was 100 kts. However, as stated above, calculations within the design tool used a value of 44 kts (30 mph) – this appears to be a simple referencing error within the design tool. The initially intended value of 100 kts appears a good initial assumption, although it is not clear from the original work whether this value was calculated or simply an initial working assumption.

3.3 Wing Loading

The wing loading was originally calculated based on two key assumptions:

- Wing reference area is equal to exposed wing area (due to flying wing configuration);
- Wing loading will be similar to that of a seaplane.

The wing area was empirically sized using the CISD Seaplane Database. The assumed weight of 45,000 lbs gave an estimated wing loading of 145 $kg.m^{-2}$. This value is used to calculate the wing area required (143 m^2). Although this offers a sensible concept level value for wing loading, this assumption should be reviewed in follow-on design iterations. It is not clear if it is realistic to assume that a flying wing design can be compared to seaplanes with more traditional wing designs.

3.4 Risks Inherent in Software

A number of assumptions are inherent in the use of Vortex Lattice Theory and, hence, in the use of the *Tornado* tool for the analysis of wing and control surface designs.

Tornado does not take into account the impacts of frictional drag, compressibility, and surface thickness on controllability. However, it is not anticipated that these effects have a significant influence on the overall analysis.

One assumption should be noted, however, when considering the outputs from Tornado. The relationship between lift and angle of attack is simple up to about the 10 degree point, after which there is a much more complex relationship due to boundary layer effects. As *Tornado* considers only inviscid flow, it can only be considered valid for small angles of attack (i.e. < 10 degrees).

4. In-Flight Control Assessment

This section overviews the analysis of the in-flight controllability of the original flying submersible concept.

During initial design, there was some focus on the in-water controllability of a flying wing concept as this was considered to be the key controllability issue. However, no in-air assessment was conducted at the time.

NOTE: the analysis shown here is based on the original data from the original study; it does reflect, therefore, some of the issues identified in the previous sections. Any further design exercise should reassess new concepts using revised data and the methodology shown below

4.1 Tornado Analysis

Tornado[2] is an open source program designed by *Thomas Melin* at the Department of Aeronautics, Royal Institute of Technology to be used in the conceptual stage of aircraft design. It is based on the standard vortex lattice theory described in the book 'Computational Fluid Dynamics' by Moran[5]. Outputs for the tool include:

- 3D forces acting on each panel;
- aerodynamic coefficients in both body and wind axes;
- stability derivates with respect to angle of attack, angle of sideslip, angular rates and rudder deflections.

It was possible to model the submersible aircraft in *Tornado* using wings made up of a series of partitions and panels. Figure 8 shows an image of the model as seen within Tornado. (Note: MAC = Mean Aerodynamic Chord)

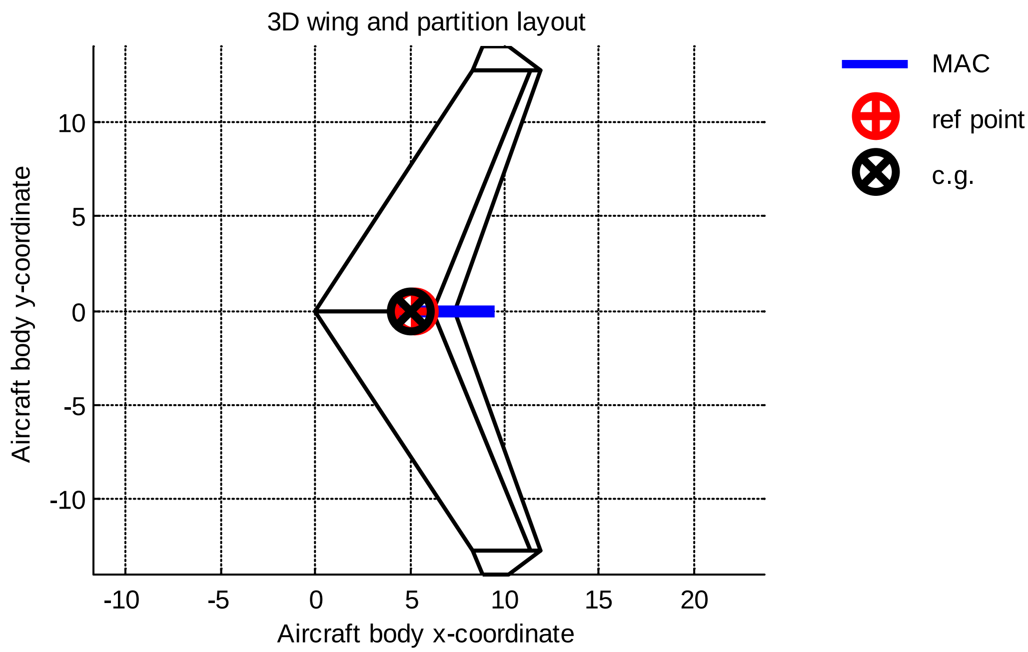

Figure 2 – Image of the fullspan_sym model in Tornado

Once the aircraft geometry has been set up correctly, the flight conditions need to be defined. The conditions used for the analysis in this report are defined below. These are saved as Cond1 within the *Tornado* flight conditions.

Cond1:

- Speed 89.408 $m.s^{-1}$ (200 mph)
- Altitude 1,524 m (5,000 ft)
- Density 1.0556 $kg.m^{-3}$
- Angle of attack 4.8298 degrees

The lattice can then be generated and analysis carried out using the *Tornado* processor.

4.2 Effect of Changes in Angle of Attack on Lift and Drag

The effect of increasing angle of attack (AoA) has on the coefficient of lift (C_L) and the drag coefficient (C_D) can be seen in Figure 3 and Figure 4 respectively. Stall cannot be seen in Figure 3 as Tornado only accurately models small angles (up to 10 degrees/0.17 radians). As stated in Section 5.1, it would be expected that the submersible aircraft concept would stall at a C_L value of approximately 1.6.

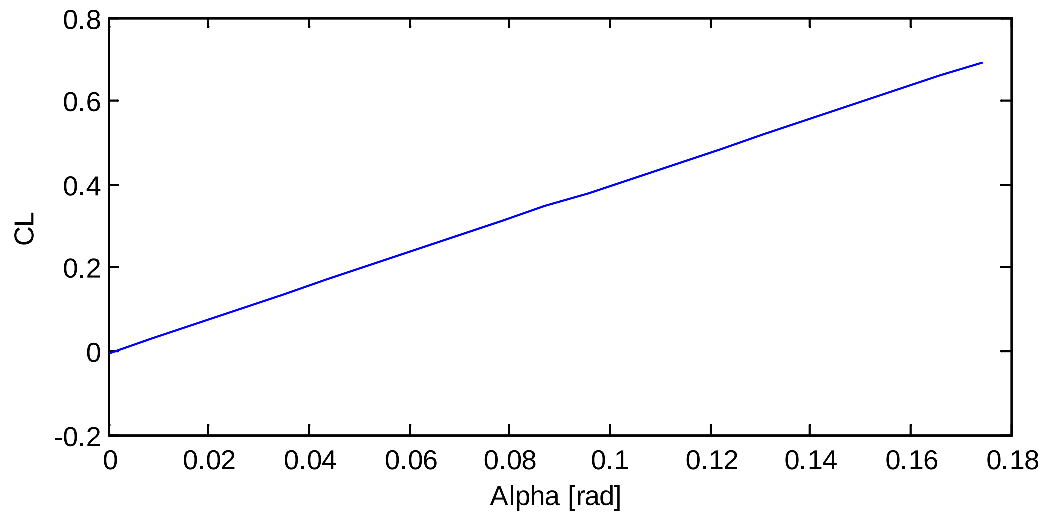

Figure 3 – Angle of attack versus C_L

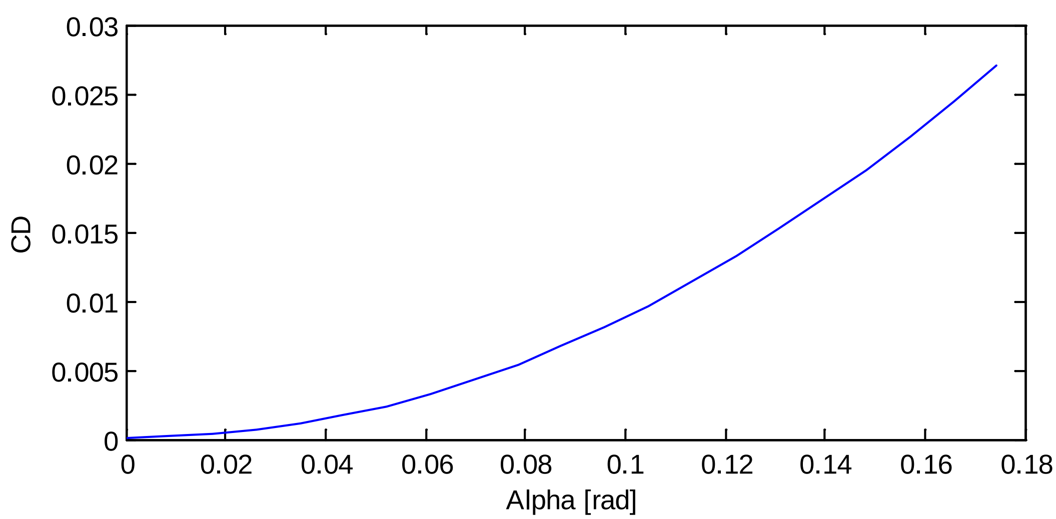

Figure 4 - Angle of attack versus C_D

The graph showing C_D variation in Figure 5 does not match the typical characteristics expected. The curve shows that the aircraft has minimum drag at a zero degree angle of attack. Figure 5 shows a typical graph for this relationship. The minimum drag is usually seen at small angles of attack and drag increases as the nose lifts or drops from that position. The rapid increase in CD is due to the flow of air separating from the surface of the airfoil. The reason for the shape of the curve in Figure 4 is uncertain, but it is possibly due to the fact that *Tornado* does not model the viscous effects of drag.

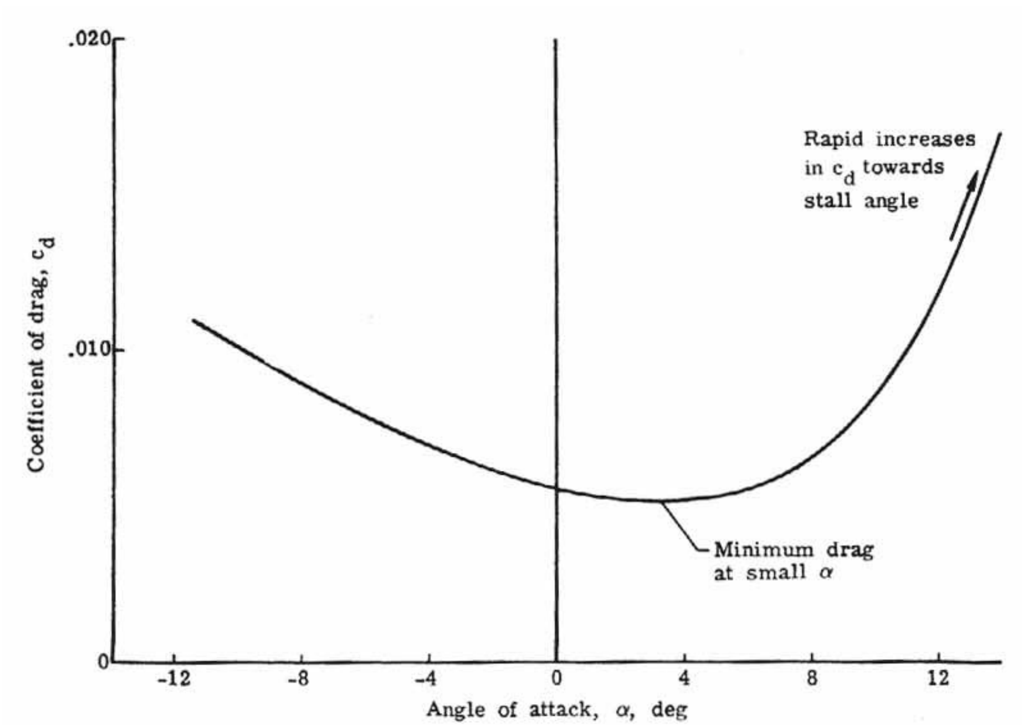

Figure 5 – Expected graph for C_D versus angle of attack

4.3 Control Methods

Roll and yaw control of the submersible aircraft are combined in the form of drag rudders. These actuate like traditional aircraft ailerons but can also be split at the trailing edge to create additional drag. Asymmetric deployment provides yaw control whilst symmetrical deployment provides a speed brake feature allowing lower landing speeds, even with a low drag airframe. Differential aileron deflections allow for coordinated turns with little to no adverse yaw. Should sideslip be desired full deflection of both aileron and rudder can be used to achieve this.

4.4 Longitudinal Stability

An aircraft is longitudinally stable when it returns to the original flight path after a disturbance.

Conventional cambered airfoils supported at the aerodynamic center pitch nose-down and, hence, have a negative pitching moment. Reflex airfoils, however, generate a nose-up pitching moment (reducing the need for a tail horizontal stabilizer). Figure 6 shows the positive values of the pitching moment coefficient (C_M) between 0-10 degrees.

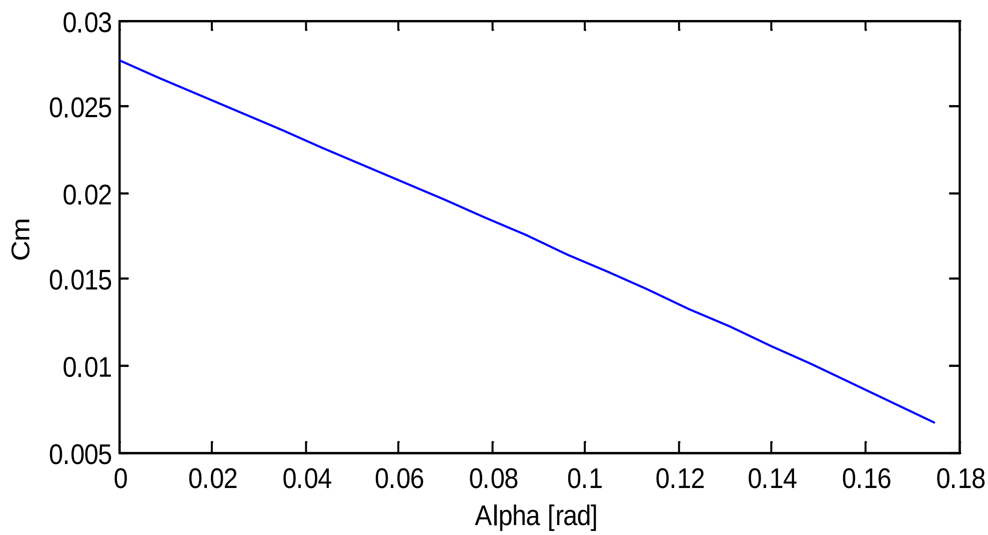

Figure 6 – Angle of attack versus pitching moment coefficient

The negative slope in the graph illustrates that the submersible aircraft is stable. For static stability, any change in angle of attack must generate moments to oppose the change. Increasing the AoA (and therefore C_L) decreases the pitching moment coefficient. This means that, after at nose up disturbance (due to gusting perhaps), the aircraft would return to its cruise attitude.

4.5 Lateral and Directional Stability

Lateral Stability is a measure of an aircraft's ability to return to its original attitude after a disturbance.

Directional stability is the ability of an aircraft to yaw into the resultant wind direction. This is also known as weathercock stability.

The design used split drag rudders for yaw control as mentioned in Section 4.5. For maximum effectiveness in roll and yaw, these need to be situated at the wing tips to increase the moment arm. Figure 7 shows the coefficients of roll and yaw against the control surface deflection. Again, only angles up to +/- 10 degrees have been considered. Higher angles of deflection will result in larger roll/yaw coefficients and, in turn, roll and yaw rate.

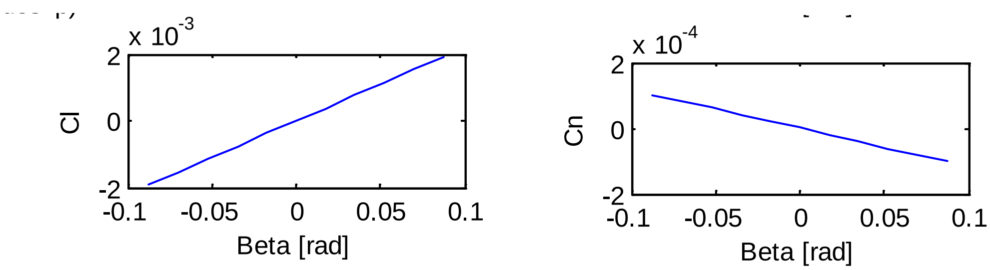

Figure 7 – Coefficients of roll and yaw versus control surface deflection angle

4.6 Control Surface Effectiveness

Different models were created in *Tornado* to determine the effectiveness of different control methods.

Figure 2, shown earlier in section 4.1, illustrates the first and second models; 'fullspan_sym', and 'fullspan_aysm'. Figure 8 shows the 'partspan_sym' and 'partspan_asym' models.

Table 5 is a summary of the different models showing the length of the flaps, the positioning of the flaps along the aircraft 'y' axis, and the flap chord as a percentage of the local wing chord and states whether the flaps deflect symmetrically or asymmetrically.

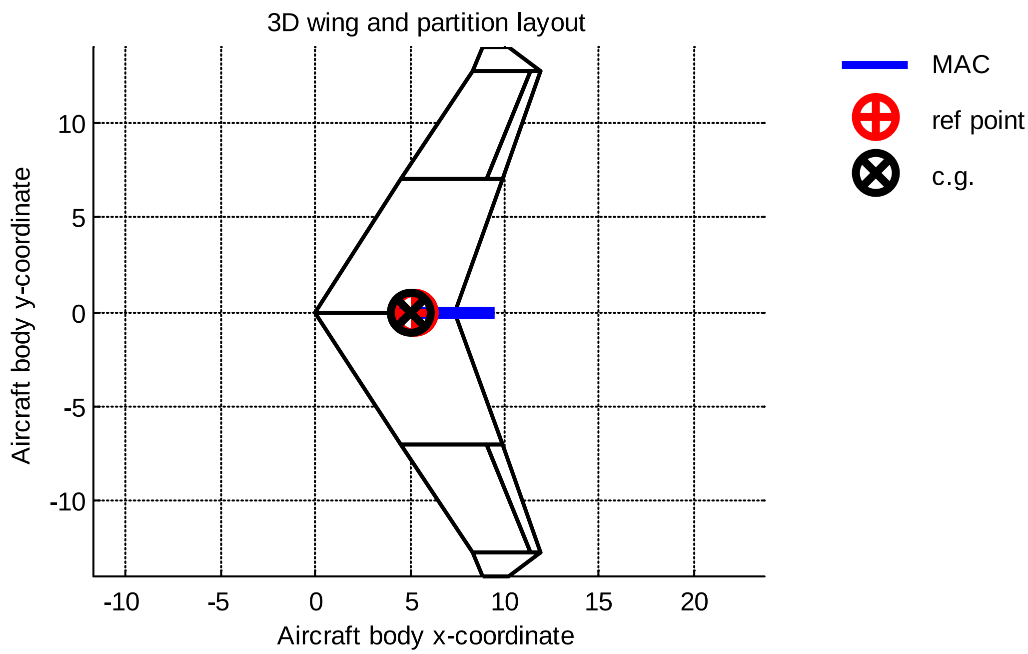

Figure 8 – Image of the 'partspan_sym' model in Tornado

Name	Flap Length (m)	Positioning	Flap Chord	Deflection Mode
A/ 'fullspan_sym'	12.72	0 < y< 12.72	0.15	Symmetric
B/ 'partspan_sym'	5.72	7 <y < 12.72	0.15	Symmetric
C/ 'fullspan_asym'	12.72	0 < y < 12.72	0.15	Asymmetric
D/ 'partspan_asym'	5.72	7 <y < 12.72	0.15	Asymmetric

Table 5 - Summary of *Tornado* control surface models

Deflecting the flaps asymmetrically simulates the drag rudders being deployed as ailerons and causes the craft to roll. Deflecting them symmetrically gives control of pitch and they act as elevators.

Modelling yaw control in *Tornado* was not possible due to the split flaps. Attempts were made to create two wings in the same design space with one having flaps that deflected in the positive direction and the other having flaps that deflected in the negative direction. Although it was possible to create a model showing the split flaps, tornado had difficulty creating the lattice and performing analysis on it. An alternative approach or software will be required to model split flap options. Detailed results from the four models follow.

Model A – 'fullspan_Sym'

The impacts of deflecting the full span flaps symmetrically from negative 10 degrees to positive 10 degrees results in the graphs shown in Figure 9.

The top left graph shows the variation in the lift coefficient (C_L) and is similar to the graph shown in Figure 3 (deflecting the elevators changes airfoil shape and, therefore, the angle of attack). As the flaps are deflecting symmetrically, they will not cause any rolling or yawing motion. This is supported by the graphs showing C_l and C_n versus angle of deflection (top and bottom right)

Pitching moment (C_m) coefficient is shown in the center right graph. As stated earlier, a change in angle of attack must generate moments to oppose the change for stability. The initial positive values of C_m are due to the reflex airfoil and would not be seen on a conventional airfoil. The negative slope shown in the graph illustrates that the craft is stable.

The center left graph shows the change in the coefficient of drag (C_D) with elevator deflection. Again, this does not show the expected trend as discussed in Section 4.2.

Changing the elevator deflection has no affect on the rolling moment coefficient, Yawing moment coefficient, or side force coefficient.

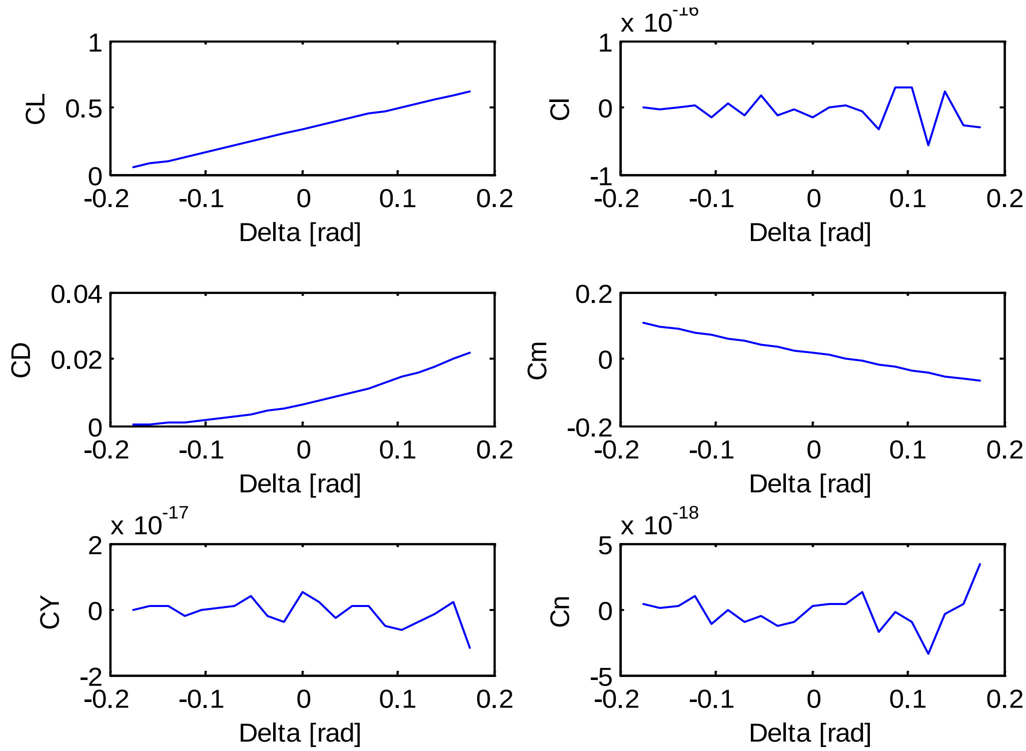

Figure 9 – Coefficient dependency of symmetric deflection of full span ailerons

Model B – 'partspan_sym'

Similar trends are identifiable in the graphs shown in Figure 10 for symmetrically deflected part span ailerons as was shown for Model A – 'fullspan_sym'. Overall values are, however, at smaller magnitudes.

Comparing Models A and B shows the impact of flap length and, hence, the effectiveness of the flap. Overall, the larger flap clearly produces more lift, a higher pitching moment, and, therefore, a faster pitching rate. Further investigation is required by using simulation software to assess whether the pitching rate of the smaller flaps meets civil/military requirements.

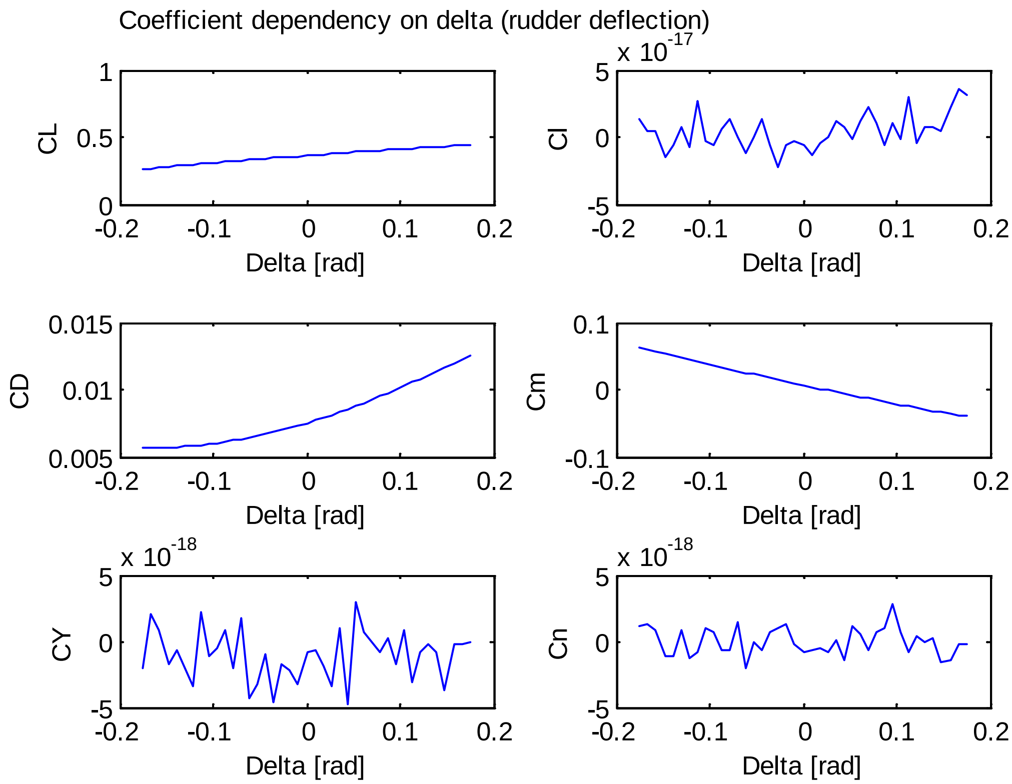

Figure 10 – Coefficient dependency of symmetric deflection of part span ailerons

Model C – 'fullspan_asym'

This concept uses flaps that can be deflected asymmetrically as ailerons, altering the span-wise load distribution so that a rolling moment about the x-axis can be produced as shown in the roll moment coefficient (C_l) in Figure 11.

A small residual yawing moment (C_n) is generated. This could be counteracted by using the split flaps to yaw in the opposite direction. However, the split flap modeling limitations already discussed prevented this being modeled within *Tornado*.

A pitching moment (C_m) is also generated which is difficult to overcome due to the fact that all controls are used for all axes of motion. The impact of this would need further investigation.

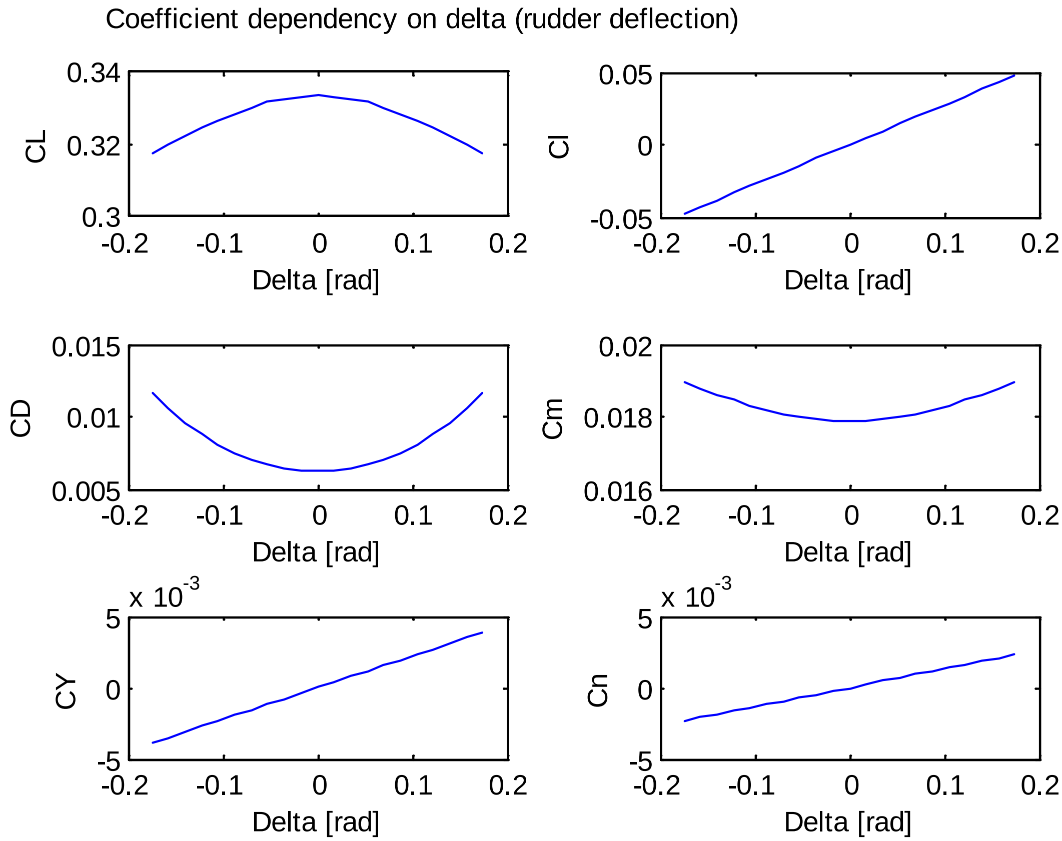

Figure 11 – Coefficient dependency of asymmetric deflection of full span ailerons

Model D – 'partspan_asym'

Again, this produces the same trends as model C – 'fullspan-asym', but at reduced magnitudes.

The magnitude of the rolling moment coefficient (C_l) is only slightly smaller than that for full span ailerons. If the results of the drag coefficient (C_D) graph can be verified, this would suggest that it may be more efficient in roll to have the smaller part span flaps rather than the full span flaps.

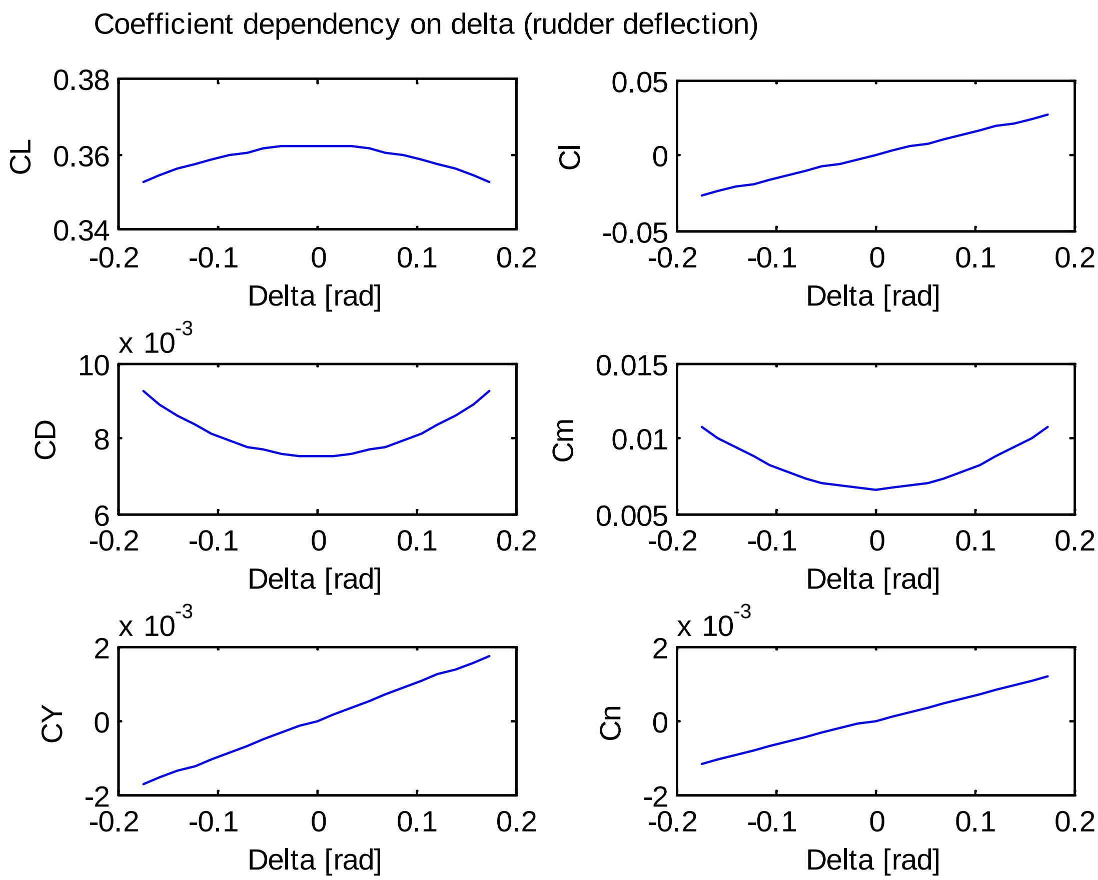

Figure 12 - Coefficient dependency of asymmetric deflection of part span ailerons

4.7 Initial Conclusions – In-Flight Control Modeling

Alternative software or modeling methods are needed to effectively model the performance of split flaps in split flap operating modes. No method was identified to accurately model this configuration within *Tornado*.

The shape of the generated coefficient of drag (C_D) curves cannot be explained if compared to typical curves. This raises concerns over the validity of the overall modeling.

Based on this assessment, it appears that a twin 'split' flap arrangement on either side of the wing is a sensible arrangement. This allows the split flaps to deflect simultaneously so that they act as one elevator. However, for yaw and roll, only the outside flaps (nearest the tips of the wings) need to be deployed, reducing the overall drag.

5. Additional Design Considerations

In undertaking the analysis discussed in section 4 and reviewing the design tool, a number of additional design consideration were raised. These are noted within this section

5.1 Stall Speed

Stall speed is important for a number of calculations including take-off distance, approach speed etc. Due to the uncertainties with the wing design mentioned in section 3, stall speed should be assessed if the wing design is changed in follow-on design iterations.

In order to calculate stall speed the following assumptions were made:

- Based on a wing loading of 145 $kg.m^{-2}$
- Uses density of air at sea level
- Uses Fig 5.3 in Raymer[1] to estimate maximum C_L. This figure is based on test results and historical data for wings of moderate aspect ratio (4-8).
- Using 30 degree wing sweep;
- Assuming the use of plain flaps;
- Gives a maximum C_L for landing of 1.6

Using Equation 1 and the assumptions listed above, a stall speed of 12.2 $m.s^{-1}$ (23.6 kts) was estimated.

The maximum C_L for takeoff is typically around 80% that when landing.

5.2 Floats – Design Observations

Seaplanes typically have 'V' shaped sections to the fuselage to reduce water impact loads. The height of the V is called 'deadrise' and has a 'deadrise angle.' The submersible aircraft concept is currently assumed to be landing on floats.

However, the geometry of the floats has not been optimized and other undercarriage methods have not been investigated in depth.

A rule of thumb for approximating deadrise angle is:

$$\alpha_{deadrise} \cong \frac{V - 20}{2}$$

Equation 2 – Deadrise angle

Using the stall speed calculated earlier (12.2 m/s for a max C_L of 1.6), this gives a deadrise angle of just 3.6 degrees. It should be increased towards the nose to about 30-40 degree to help it cut through the waves. Spray strips could be added to minimize spray impingement.

6. Conclusions and Recommendations

The original submersible aircraft study undertook a considerable level of analysis and design work within a relative short period of time in order to produce a balanced design. To achieve this, a number of initial assumptions were made and a new design tool developed. A number of calculation/design risks were inherent in the initial design. This short study sought to assess these risks and to undertake an initial assessment of the controllability aspects of the proposed designs.

This report has highlighted some of the key risks identified in a review of both the basis design assumptions and the tool developed to create the initial designs. The following conclusions and recommendations are made.

- A further design iteration needs to be conducted to reflect the issues identified within this report. This second design iteration should consider:
    - a review of key assumptions reflecting the comments made in Section 3 of this paper to include, but not be limited to, the maximum take-off weight, take-off and cruising speeds, and altitude assumptions;
    - validation of the weight estimate particularly focusing on the estimates used for the hydraulic and battery systems;
    - changes to the wing design to reflect weight, speed, and angle of attack issues highlighted in Section 3;
    - the potential integration of floats into the wing design.
- A further iteration of the in-air control analysis reflecting any changes made in the further design iterations. This analysis should extend to consider in more detail issues such as lateral stability, longitudinal and lateral dynamics (e.g. assessing the aircrafts ability to recover from spin), and stall.
- Initial assessments in this study suggest that a split flap arrangement should offer the most flexible solution for the craft, and that shorter flap lengths may produce the

required control but at a higher efficiency. More detailed analysis is needed to verify this conclusion. Noting the limitations of *Tornado* with respect to the unusual coefficient of drag versus angle of attack plots and the inability to model spilt flap operations, alternative software and modeling solutions should be considered to undertake this analysis.

- The potential to input designs into flight simulation software should also be considered. This would provide a more graphical way to visualize some of the control features and control performance.

7. Proposed Further Work

- To take the concept forward, further design iterations are required. These should take into account the comments, issues, and changes discussed and proposed in this report.

- It would be useful to develop a drag estimation tool for in-flight operations. The current underwater drag estimation section within the design tool would be good basis for its development.

- A number of float design options were considered in the original study. These need to be considered in greater depth and should also consider the possibility of integrating the floats into the wing design.

- It is feasible to export design concepts into a flight simulation software package such as Xplane. This would allow virtual 'flight testing' of concepts and, hence, provide the ability to assess the stability and control of the design including in complex scenarios such as stall and spin without potentially damaging or rebuilding physical models.

8. References

(1) *Submersible Aircraft Concept Design Study*, J. Eastgate and R. Goddard, NSWCCD-CISD-2010/011, August 2010

(2) http://www.redhammer.se/tornado/index.html

(3) *Aircraft Design: A Conceptual Approach*, Daniel P. Raymer, AIAA, 1992

(4) *Notes on the Stability and Control of Tailless Airplanes,* Robert T. Jones, NACA Technical Note No.837, December 1941

(5) Moran, J., *Computational Fluid Dynamics*, Wiley & Sons, 1984.

(6) www.centennialofflight.gov/essay/Theories_of_Flight/Two_dimensional_coef/TH14G5.htm

9. Acknowledgements

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Appendix 1 - Summary of Changes to *Design Tool*

This section captures design changes made to the Excel based *Submersible Aircraft Design Tool* to provide traceability for future design work and reflects some of the errors found in the tool.

Each of these tables starts with a change to a value in the cell listed in row 1. Dependents are then followed through in the remainder of the tables to find the impact that changing the value had on the design

Worksheet	**Cell**	**Original Value**	**New Value**	**Comments**
InputOutput	D9	= D7*1.46666667	168.781	Dependents: ‘Initial Wing Weight and Volume’ G13, ‘TurboFanProp Fuel Calc’ C5
Initial Wing Weight and Volume	G13			No dependents.
TurboFanProp Fuel Calc	C5	=InputOutput!D7	=InputOutput!D9* 0.681818	Dependent: ‘TurboFanProp Fuel Calc’ H32 H36
TurboFanProp Fuel Calc	H32			Used to calculate fuel required for turboprop – therefore not required
TurboFanProp Fuel Calc	H36			Used to calculate fuel required for turboprop – therefore not required

The spreadsheet is set up to use values from the underwater drag estimate in further calculations. This is not obvious using the ‘trace dependents’ function as the workbook uses Macros. The drag calculation in flight would be done in the same way.